Redatuming and deghosting of variable-depth streamer data

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Summary

The frequency of ghost notch is naturally diversified by random variations at the sea surface. Further diversity may be achieved by towing a variable depth streamer. Regardless of the streamer shape however, the recorded seismic data needs redatuming and deghosting with respect to both ray parameter and individual source and receiver depths. We present a slowness-variant redatuming and deghosting method, capable of handling variable depths and irregular offsets. We utilize fine-tuned depths for deghosting and estimated elevations for redatuming. The effectiveness of the presented method has been validated by application to field data acquired by various configurations including flat, slant and curved streamers.

Introduction

Broadband seismic data is desirable for interpretation purposes. In a marine environment however, the spectrum of recorded seismic signal is governed by a number of factors including the interference of the ghost reflections. Attempts are made to improve both temporal and spatial resolution of seismic data in both acquisition and processing stages. Recent developments in the acquisition stage include dual-sensor streamers (Carlson et al., 2007), over-under streamers (Özdemir et al., 2008), variable-depth streamers (Soubaras, 2010) and multicomponent streamers measuring pressure and the gradient wavefields (Vassallo et al., 2013). In the processing stage a number of techniques have been introduced aiming to deghost the data either before, while, or after the migration process. A premigration deghosting method was proposed by Wang and Peng (2012). Zhou et al. (2012) applied a deghosting process on conventional streamer data. Masoomzadeh et al. (2013) proposed a method of angle-dependant redatuming and deghosting for slanted streamers, assuming a flat sea surface. Robertsson and Amundsen (2014) developed a finite-difference method for deghosting streamer data towed at arbitrary variable depths. In this paper we propose a method of redatuming and deghosting applicable to seismic data acquired by single-sensor variable-depth streamers in presence of sea surface undulations.

In practice, neither the sea surface is flat nor do the receivers remain in predefined depths. As can be seen in Figure 1, the receiver depths are constantly changing, even during the listening period. This level of variation results in a 'natural' diversity of nonzero notch frequencies. This nearly random diversity means that the weak signals surviving the destructive ghost interference in the vicinity of the nominal notch frequencies can be further suppressed by the stacking process.

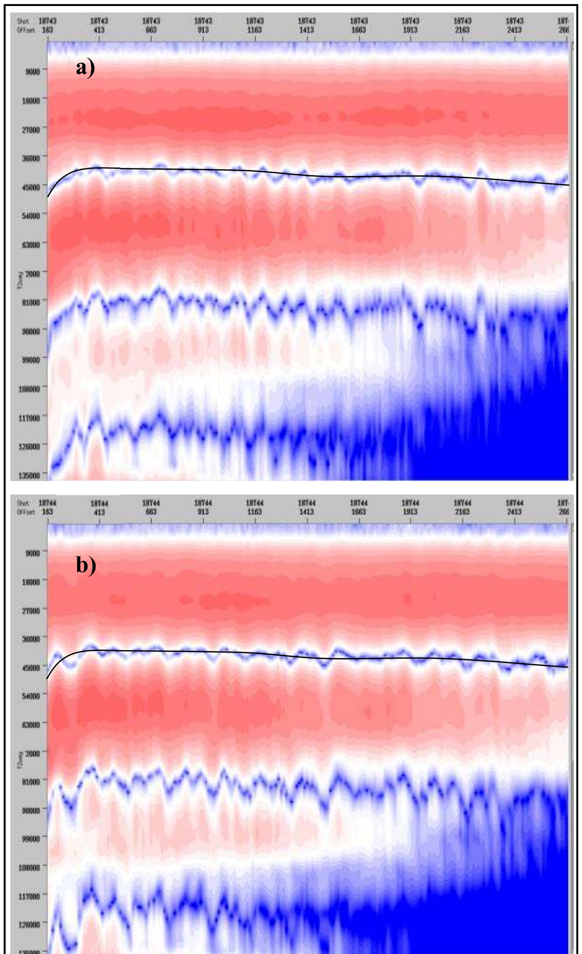

Figure 1: a) Amplitude spectra of traces from a shot gather acquired at a nominal depth of 18 m, obtained after the water-bottom event is approximately isolated and NMO corrected. It can be seen that the notch frequency is inconsistent along the streamer length, due to the variation of the sea surface and the streamer shape. b) Amplitude spectra of the next shot gather, which present a completely different trajectory of notch frequencies compared to a). Local variations may be attributed to the surface undulations while the global feature (black curve) can represent the actual streamer shape.

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Figure 2 shows the phase discrepancy for a narrow band around the first receiver notch caused by the random variation of receiver depths. As a result of this inconsistency, even after a successful prestack deghosting, there is a chance that the stacking process could reintroduce a secondary notch at the centre of a frequency range in which the phase discrepancy is significant (Figure 3). This secondary loss of signal can be observed more often on the shallow events where stacking velocity is close to the water velocity, so that primary and ghosts are almost parallel after the NMO correction. This secondary notch effect may no longer be observable when a variable-depth streamer is used, because the discrepancy can be diversified over a wider range of frequencies.

Although in practice a flat streamer may not be achievable, the term variable-depth is often used to refer to a case in which the streamer is deliberately towed in a desired nonflat shape. The streamer can be simply slanted linearly (Bearnth and Moore, 1989; Dragoset, 1991), or can be given a desired nonlinear shape (Soubaras, 2010). It is important to note that merely towing a streamer in a nonflat shape we do not attenuate the receiver side ghosts, we only diversify them, and therefore we may wish to redatum and deghost the data prestack and premigration.

Regardless of the streamer shape, it is possible to use processing techniques to redatum the recorded data and attenuate the ghosts. Masoomzadeh et al. (2013) introduced a method of redatuming and deghosting applicable to the data acquired by a linearly-slanted streamer. In this paper we introduce a more advanced method where both the elevation and the actual depth of every individual receiver are taken into account.

Normally at the time of acquisition the actual depths of a subset of receivers are measured. These measured depths are then interpolated and extrapolated to estimate a depth value for each receiver. In case these estimated values are not available or too inaccurate, we may try estimating or validating them using the information present in the seismic data.

Using the amplitude spectra shown in Figure 1, we may search for the lowest amplitude in the vicinity of estimated notch frequency to estimate the effective depth of individual receiver groups. Alternatively, we can perform a stochastic search to find an optimum set of parameters minimizing the ringing effect in the autocorrelation of a shallow window of every trace. These estimated depths can be useful for the deghosting operation; for the redatuming purpose however, we consider smoothing those rapid variations attributed to the sea surface undulations, in order to estimate receiver elevations from the Mean Sea Level.

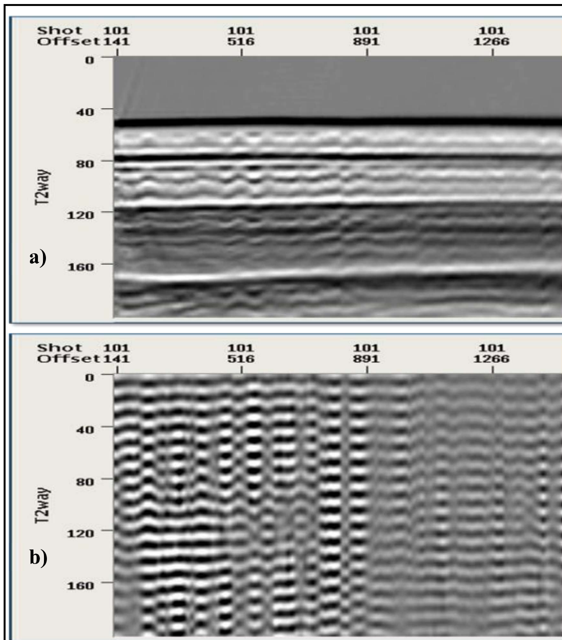

Figure 2: Near offset part of a shot gather acquired by using a flat streamer after deghosting based on nominal source and receiver depths. a) Residual ghosts can be observed below the primary events. b) A filter applied to pass a narrow band around the first receiver notch reveals the phase discrepancy due to receiver depth variation along the streamer.

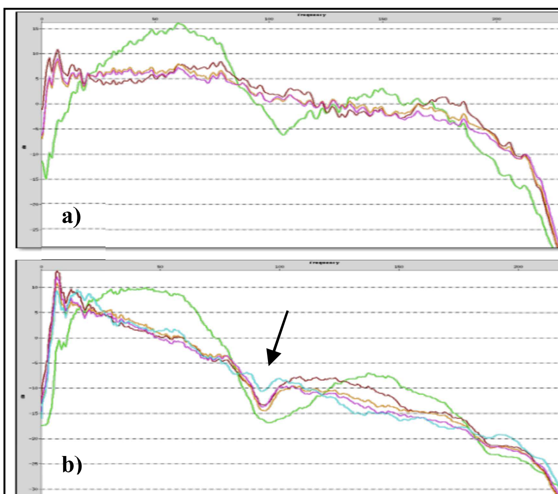

Figure 3: Average Amplitude spectra before (green) and after deghosting: a) before stack, b) after stack. Some amplitude loss is observed around a frequency at which the maximum phase discrepancy occures (pointed by an arrow). This effect is more observable around the seabed event, where the stacking velocity is closer to the water velocity.

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Redatuming and deghosting of variable-depth streamer

Figures 4 and 5 illustrate the redatuming and deghosting operations respectively. For a receiver group located at the offset of x, we assume that z_x is the elevation from the MSL datum (negative below the datum) and d_x is a positive value representing the actual depth from the water surface, where the water velocity is v_w. The effect of the discrepancy in the shape of sea surface reflector is implicitly taken into account by assuming a frequency- and angle-dependant reflection coefficient of $r(\omega,p)$ at the sea surface.

Beginning with a multichannel shot record in the time-offset domain, we first transform every trace into the frequency domain (U_x). Then for every temporal frequency sample we apply either or both redatuming and deghosting operators. These operators are designed based on individual receiver elevations and depths, in conjunction with a specific horizontal slowness of p. Then we can perform a slant-stacking process to obtain those particular slowness traces for which the operations described above were reasonably accurate ($U_{\pm p}^{RD}$). After scanning over a desired range of p values we can perform an inverse transformation to obtain a redatumed and deghosted wavefield back in the time-offset domain.

Following equations provide a mathematical expression of the method explained above:

$$\cos\theta = \sqrt{1-p^2 v_w^2}\,, \tag{1}$$

$$U_x^R = U_x e^{-i\omega z_x \cos\theta / v_w}\,, \tag{2}$$

$$U_x^{RD} = U_x^R\left(1 + r(\omega,p)e^{2i\omega d_x \cos\theta/v_w}\right)^{-1}, \tag{3}$$

$$U_{\pm p}^{RD} = \sum U_x^{RD} e^{\mp i\omega p x}\,. \tag{4}$$

In case the offset increment is regular, we may accelerate the technique by using Fourier transformation in the offset direction instead of slant-stacking. In this case, instead of creating a pair of p-traces we create a pair of k-traces in each iteration. In other words, since $k=\omega p$, Equation (4) gives:

$$U_{\pm k}^{RD} = \sum U_x^{RD} e^{\mp ikx}\,. \tag{5}$$

Compared to the techniques developed for the flat and linearly slanted streamers, this method requires more computational effort; because it involves applying two operations to every offset trace in order to obtain each redatumed and deghosted component, before an inverse transformation can be performed.

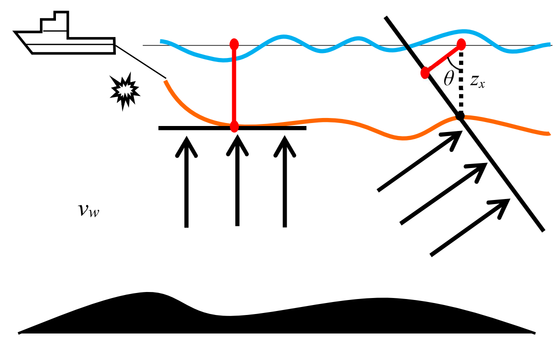

Figure 4: Schematic diagram of redatuming seismic wavefields recorded by a curved streamer to the Mean Sea Level. A time shift of $z_x\cos\theta/v_w$ acknowledges both elevation of every individual receiver, and the angle of each plane-wave component. Every slowness trace is obtained via slant-stacking, after redatuming all contributing traces accordingly.

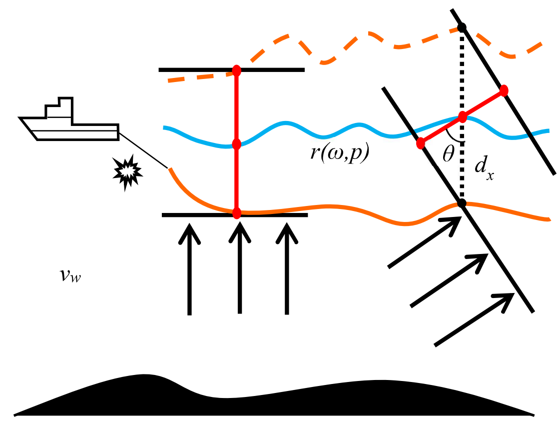

Figure 5: Schematic diagram of deghosting seismic wavefields recorded by a curved streamer. A time delay of $2d_x\cos\theta/v_w$ takes into account both the depth of every individual receiver, and the angle of each plane-wave component. Every slowness trace is obtained via slant-stacking, after deghosting all contributing traces accordingly.

In practice we can use the Fast Fourier Transformation (FFT) algorithm to quickly calculate a full range of k-traces, retaining those traces for which the performed operation is reasonably accurate. Further speed up is

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achieved by dividing the input gather into a number of overlapping subpanels. We apply a square root of cosine taper to the edges of each subpanel before application of the main process, and reapply similar tapering afterwards, before merging the processed subpanels back into a full gather.

In case of 3D survey, assuming that the offset increment in both x and y (i.e. inline and crossline) directions are small enough, or if it is possible to interpolate traces in order to prevent spatial aliasing, we may consider using 3D transformations, for example into the ω-p_x-p_y domain, where $p^2=p_x^2+p_y^2$, or, into the ω-k_x-k_y domain, where $k^2=k_x^2+k_y^2$. In the case of large and irregular offset increment in either or both directions, a high-resolution *tau-p* transformation or anti-leakage Fourier transformation can be used to control the issues introduced by the aliasing effect.

In the presence of complex geology, this technique can be applied to the shot gathers, aiming to deal with the receiver side. A second pass of similar operations can be applied to the common-receiver location gathers in order to handle both redatuming and deghosting in the source side, acknowledging any possible variations of source elevations and depths.

Figure 6 shows part of a shot gather acquired by a variable-depth streamer, which was deviated from its intended linear trajectory due to some practical limitations. In this case the initial deghosting attempt created some ringing, due to the violation of linear shape assumption. The new method however, demonstrated impressive capability to overcome this situation.

Conclusions

We present a method for both redatuming and deghosting of marine seismic data acquired by single-sensor variable-depth streamers. This method is capable of handling irregular absolute-offset increment, often associated with the lateral offset of outer streamers in a 3D wide-azimuth survey. Accurate redatuming means we virtually move all sources and receivers to the Mean Sea Level. Therefore, conventional processing techniques historically designed for flat streamer data, including many demultiple techniques, velocity analysis and NMO correction, remain valid and applicable. For the purpose of redatuming we use a smoothed representation of receiver depths to exclude the short-wavelength local variations in the sea surface. Regardless of the streamer shape, using a measured or estimated depth for every receiver group improves the deghosting outcome. Further enhancements may be achieved by fine tuning those estimated depths.

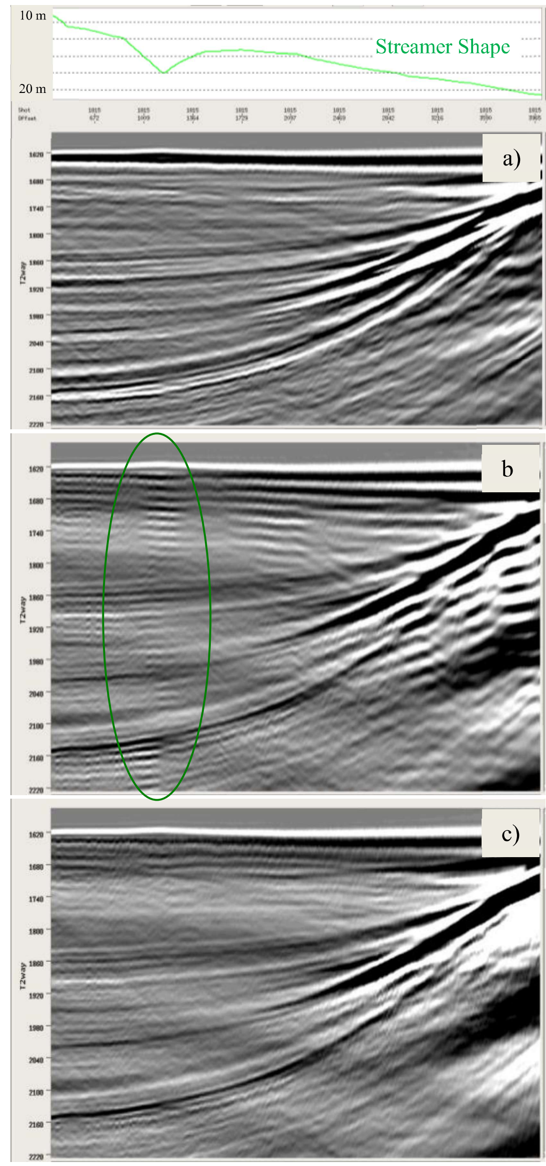

Figure 6: A shot gather acquired by a shaped streamer, a) before deghosting, b) after deghosting while falsly assuming a linear streamer shape, which results in some ringing effect due to inaccurate deghosting. c) After deghosting while acknowledging the streamer shape, showing noticeable reduction of that effect.

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EDITED REFERENCES

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